CONTRIBUTIONS TO THE THEORY OF ALPHA DECAY

BY

PER OLOF FRÖMAN

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ALMQVIST & WIKSELLS BOKTRYCKERI AB

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Inaugural Dissertation

by

PER OLOF FRÖMAN
Fil. lic., Småland

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The nature of the alpha decay process was for many years a great mystery, but in 1928 Gamow and, independently, Condon & Gurney explained the alpha decay as a quantum mechanical penetration of an alpha particle through the potential barrier around the nucleus. The most striking result of this alpha decay theory, which was based on a very simple spherical model for the atomic nucleus, was the derivation of a formula connecting the atomic number, the nuclear radius, the half-life, and the alpha particle energy. This connection was in very satisfactory agreement with the empirical Geiger–Nutall law which had then been known for several years.

In 1930 Rosenblum discovered the alpha fine structure which is due to the fact that the daughter nucleus may be left in different energy levels. The numerous experimental investigations concerning the alpha fine structure which have been done later, especially during the last decade by Perlman and co-workers, have shown many regularities in the alpha fine structure, but they have also shown the need for an extension of the alpha decay theory.

The ideas about the structure of heavy nuclei, which have been developed by Bohr & Mottelson, form a promising starting point for the explanation of the details of alpha decay. Along these lines theoretical aspects of the alpha fine structure are considered in the following two papers:

A. Bohr, P. O. Fröman, and B. R. Mottelson, On the fine structure in alpha decay, *Mat. Fys. Medd. Dan. Vid. Selsk.*, *29*, no. 10 (1955),

Per Olof Fröman, Alpha decay of deformed nuclei, *Mat. Fys. Skr. Dan. Vid. Selsk.*, *1*, no. 3 (1957),

which form the basis for this thesis.

In the first paper the concept of "favoured" alpha groups is extended. This special type of alpha decay has an especially great intrinsic probability to occur, but due to the strong energy dependence for the penetration probability of the alpha particle through the potential barrier, the actual intensities of the favoured alpha groups may be much smaller than for unfavoured transitions corresponding to larger alpha particle energies. By correcting the observed transition probabilities for the strong energy dependence due to the potential barrier one can define reduced transition probabilities which give information about the intrinsic alpha transition probabilities. This reduction of the alpha transition probabilities is conveniently based on the empirical connection between atomic number, transition probability, and alpha particle energy for the ground state alpha transitions of even-even nuclei. For these transitions the logarithm of the transition probability can be represented, with good approximation, as a linear function of the reciprocal of the square root of the alpha particle energy, the two coefficients being functions of the atomic number only. This formula may be considered as a refinement of the Geiger–Nutall law. The numerical values of the reduced transition probabilities make it in general possible to select for every given nucleus of odd mass number the favoured alpha transition which corresponds to no change of spin and parity for the nucleus. These special transitions have been determined for the alpha radioactive isotopes for which sufficient data were available when this work was done. If one plots the energies of these special alpha transitions in nuclei of odd mass number, one obtains points lying very regularly with respect to the corresponding points for the ground state alpha transitions in even–even nuclei. For some nuclei of odd mass number one can identify two or more favoured alpha transitions for the same nucleus. The relative intensities of the favoured alpha groups can be calculated approximately on the basis of the empirical data for the intensities of the alpha transitions to the different

states of neighbouring even–even nuclei. The calculated relative intensities are in satisfactory agreement with the corresponding empirical intensities.

In the second paper a general theoretical treatment is given of the problem concerning the penetration of an alpha particle through the anisotropic potential barrier around a deformed nucleus described by the unified nuclear model. The wave function for this problem is so constructed that it corresponds to a given initial state of the parent nucleus and that it can describe transitions to the different possible final states of the daughter nucleus. This wave function, which automatically fulfills the conservation laws for energy, momentum, and angular momentum, contains for every possible final state of the daughter nucleus a radial wave function which depends on the distance between the alpha particle and the center of the daughter nucleus. From the Schrödinger equation one obtains for these functions a system of coupled ordinary differential equations of the second order. Similar differential equations have also been considered by Rasmussen & Segall in Berkeley and by Strutinsky in Moscow. Very accurate solutions of the equations can be obtained only by numerical methods. For the present time it seems, however, to be more useful to aim at approximate analytical formulae which make it possible to survey the general features of the problem. Such formulae for the radial wave functions are obtained in terms of the alpha wave function on the nuclear surface. Formulae for the transition probabilities and the angular distributions of the alpha groups corresponding to transitions from the given initial state of the parent nucleus to the different possible states of the daughter nucleus are then given. By means of these formulae the following results are obtained.

The deformation of an alpha radioactive nucleus gives rise to an enhancement of the alpha decay rate, as was first pointed out by Hill & Wheeler. An improved estimate of this enhancement shows that it can amount only to a factor of about two. A factor of only

this order of magnitude and varying slowly with atomic and mass numbers is difficult to trace in the empirical data.

The data on the transition probabilities for the alpha fine structure components of even–even nuclei make it possible to draw some conclusions about the effective shape of the nuclear surface. This effective shape reflects not only the actual nuclear shape but also the angular dependence of the alpha wave function on the nuclear surface. The probability for the alpha transition going to the nuclear state 2 + depends essentially on the quadrupole deformation of the nucleus and is of the order of magnitude which one expects from the known value of this deformation and the assumption that the alpha wave function is approximately constant on the nuclear surface. Empirically one does not yet know anything about the higher multipole deformations, but the interpretation of the alpha decay data indicates the presence and variations of such higher deformations (or corresponding behaviour of the alpha wave function on the nuclear surface).

A detailed treatment is given of the previously mentioned formula for the approximate calculation of the relative transition probabilities for the favoured alpha groups of nuclei of odd mass number on the basis of the transition probabilities for the alpha groups of neighbouring even–even nuclei.

The problem concerning the angular distribution of the alpha particles from polarized parent nuclei is considered.

A systematic analysis of the empirical alpha decay data is also presented. A similar analysis, which partly contains quite recent unpublished data, has been made by Perlman & Rasmussen.